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Evaluating carbon footprint of municipal solid waste treatment: Methodological proposal and application to a case study

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ABSTRACT

This paper applies the Life Cycle Assessment methodology to develop a simple method to calculate the carbon footprint of the municipal solid waste treatment stage. This simple and structured methodological procedure takes into account: i) direct greenhouse gas emissions produced in waste treatment, taking place within the city boundary (scope 1 of international carbon footprint standards); ii) indirect greenhouse gas emissions related to the use of grid-supplied electricity, as well as fuel production and distribution (scopes 2 and 3 emissions as per international carbon footprint standards); and iii) avoided greenhouse gas emissions as a result of the products obtained (if any) that can replace other products or the raw materials used to produce them. Madrid City (a representative European city), the capital of Spain, was used as a case study to prove the validity and usefulness of the proposed methodology. In this city, 344 kg of municipal solid wastes were produced per inhabitant in 2013. These wastes were collected separately in different fractions (packaging, glass, paper/cardboard and mixed waste, including organic material). Mixed waste and packaging fractions were processed at the Valdemingómez Technology Park. The current treatment stage was compared with several alternative scenarios which describe hypothetical management routes for the different waste fractions. The carbon footprint for the current situation is equal to 224 kg CO_2 eq/t_{waste}. In comparison to the worst situation, corresponding to the scenario in which municipal wastes were landfilled without energy recovery, the current scenario reduces its carbon footprint by 1597 kg CO_2 eq/t_{waste} (a reduction of 88%). Improvements in the material separation and recovery processes, along with the implementation of biological treatments for the organic fraction, clearly contribute to reducing the carbon footprint of the municipal solid wastes handled in the city of Madrid.

According to the obtained results, the scenarios based on a total recovery of valuable materials and waste-to-energy or anaerobic digestion treatments present the lowest carbon footprint because burden avoided is more important than direct and indirect emissions from treatments. In addition, the consumption of electricity and the emissions derived from its generation (mix of generation), can increase the carbon footprint of power-intensive treatments.

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1. Introduction

The European Commission (EC) has set out different priority actions to optimize Municipal Solid Waste (MSW) Management (MSWM) in Europe, which are expected to bring environmental benefits as well as financial savings and social advantages.

The Waste Framework Directive –WFD– (EC, 2008) establishes a legally binding, five-step hierarchy, setting out an order of priorities, starting with 'waste prevention' as the preferred option, followed by 'preparing waste for reuse', 'recycling' and 'other recovery' (e.g. energy recovery), with 'disposal' being the last choice. According to EC (2008), the member states and their municipalities have to "*take measures to encourage the options that deliver the best overall environmental outcome. This may require specific waste streams departing from the hierarchy where this is justified by Life Cycle Thinking (LCT) on the overall impacts of the generation and management of such waste*".

The LCT concept and quantitative tools such as Life Cycle Assessment (LCA) can provide an informed and science-based support to more environmentally sustainable decision-making in

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MSWM (Manfredi et al., 2011), as demonstrated in Laurent et al. (2014).

The LCA methodology can be applied to calculate the emissions of greenhouse gases (GHG) associated with MSW treatments (Lee et al., 2017), thus evaluating the environmental impact (EI) in terms of climate change (CC) for each of the existing technological solutions, that is, the calculation of Carbon Footprint (CF).

The aim of the article is to propose a simple methodology to calculate the CF of MSW treatment stage, built from the reviewed literature and using a consequential LCA approach (Bernstad Saraiva et al., 2017). This methodology can contribute to assess CF of cities under conditions of limited information (Fry et al., 2018). In addition to direct emissions (AM, 2015a), the methodology considers indirect (BSI, 2013, 2011; WRI, 2014) and avoided emissions (Fei et al., 2018; Ferreira et al., 2017). It takes into account emissions from the conventional MSW fractions (mixed waste - including organic material/fraction (OF) -, packaging, paper and cardboard, and glass) and their composition, as a key factor to define MSWM solutions (Bisinella et al., 2017).

Abbreviations a-GHGe, avoided greenhouse gas emissions; aR, all recycling; B, biomethanization; C, composting; CC, climate change; CF, carbon footprint; d-GHGe, direct greenhouse gas emissions; DOC, degradable organic carbon; EC, European Commission; EEA, European Environmental Agency; EF, emission factor; EI, environmental impact; EU, European Union; F1, mixed waste; F2, packaging; F3, paper and cardboard; F4, glass; FC, fossil carbon; Fi, methane/biogas volume fraction; GHG, greenhouse gases; GWP, global warming potential; I, incineration; i-GHGe, indirect greenhouse gas emissions; IPCC, International Panel on Climate Change; L, Landfill/Landfilling; LCA, life cycle assessment; LCI, life cycle inventory; LCIA, life cycle impact assessment; LCT, life cycle thinking; LwBr, landfilling without biogas recovery; MBT, mechanical-biological treatment; MCF, methane correction factor; MSW, municipal solid waste; MSWM, municipal solid waste management; OF, organic fraction; OX, oxidation factor; R, recycling; RDF, refuse-derived fuel; SA, sensitivity analysis; SP/MRF, sorting plant and material recovery facility; VTP, Valdemingómez Technology Park; WFD, Waste Framework Directive; WtE, waste-to-energy.

The methodology was applied to Madrid as an example of a typical European city. No similar methodologies have been previously applied to this geographical area. The current situation was compared against nine alternative scenarios, based on recent studies, their results and conclusions. Thus, Ardolino et al. (2018) carried out an LCA study that quantifies and compares the potential EI of an anaerobic digestion plant, where the produced biogas is upgraded to biomethane for the transport sector instead of being directly burned in a combined heat and power unit. This study shows the overall environmental sustainability of biomethane production by anaerobic digestion of the separately collected OF from MSW. Bernstad Saraiva et al. (2017) compared three management alternatives for OF from MSW using LCA methodology: a) landfill, b) selective collection of for anaerobic digestion, and c) biomethanization after post-separation of. Erses Yay (2015) conducted a study in Sakarya (Turkey) using LCA methodology. They showed that landfilling and incineration were the worst waste final disposal alternatives in terms of CF, while composting and material recovery showed better performance. Fei et al. (2018) analyzed and compared three MSWM options, showing that raw MSW landfill was the worst management option. Incineration had higher energy efficiency, and mechanical-biological treatment (MBT) had the highest energy efficiency when connected with biogas purification systems, and could avoid pollution more significantly than the other two technologies. Fernández-Nava et al. (2014) analyzed six strategies for managing the MSW generated in Asturias (Spain). The study concluded that biomethanization contributes to reducing the impact in CC. Ferreira et al. (2017) analyzed the packaging waste management system in Belgium. A comparison between two scenarios was developed: the first one comprised the MSWM operations envisaging the recycling of packaging materials, and the second one was developed based on the hypothesis that there was no recycling system and all packaging waste was collected in the refuse collection system. The results were consistent with the hypothesis that the recycling scenario is more environmentally sound. Lee et al. (2017) evaluated landfill GHG emissions and the influence of key parameters depending on MSW stream. Montejo et al. (2013) assessed the environmental performance of MBT plants and results indicated the strong dependency with both energy and materials recovery efficiency. They also included a recommendation for upgrading and/or commissioning of future plants: to optimize materials recovery increasing automation during selection, and to prioritize biogas-electricity production from the OF through direct composting.

The alternative scenarios used as examples to validate the proposed methodology are based on these recent studies and their results, and combine the following treatments: waste-to-energy (WtE) plants, composting, biomethanization (obtaining biomethane to be used as fuel) and landfilling. Some of these scenarios have been established in line with the concept of the circular economy (EEA, 2016).

This paper is one of a three-part investigation aimed to propose methodologies and evaluate the CF of the different stages of MSWM, taking Madrid city as a case study. In the first one, Pérez et al. (2017a) analyzed the CF of the pre-collection stage. In the second one, Pérez et al. (2017b) focused on MSW collection and transport stages. Our methodology was applied to the truck fleet of Madrid under different scenarios. Finally, this paper shows an in-depth assessment of the CF of the treatment stage.

2. Material and methods

2.1. Case study

The city of Madrid is used as a case study to apply and contrast the methodology. Table A1 (Appendix) shows its main macroeconomic data and an overview of its relevance compared to the rest of Spain.

MSW generated in the city are managed by the Madrid City Council, which is responsible for its collection, transport and treatment. They are collected separately into four main fractions (Fig. A1, Appendix): mixed waste (F1, including OF), packaging (F2), paper and cardboard (F3) and glass (F4). In addition, there are specific collection routes for other kinds of waste: batteries, clothes, etc. (AM, 2014a, b).

F1 and F2 are specifically treated at the Valdemingómez Technology Park (VTP), the city's integrated waste management center. Plants and treatments implemented are as follows:

- Las Lomas: sorting plant and material recovery facility (SP/MRF) for F1 and incineration (I) plant with energy production: WtE plant
- La Paloma: SP/MRF for F1 and F2 and biomethanization (B)
- Las Dehesas: SP/MRF for F1 and F2, composting (C), B and operational landfill (L) with biogas recovery
- La Galiana: sealed landfill with biogas recovery and energy valorization of biogas to produce electricity

F3 is transported directly to recyclers, while F4 is taken to

recyclers after passing through the VTP transfer station (Pérez et al., 2017a, b).

2.2. Description of scenarios

2.2.1. Current scenario

This scenario corresponds to the MSW treatment for 2013, as a characteristic year of the MSWM in the city (the current treatment scheme remains unchanged since then and the data is publicly available for this year). Fig. 1 shows the different waste flows in VTP for these fractions, detailing inputs and outputs of each treatment.

F1 enters into Las Lomas, La Paloma and Las Dehesas SP/MRF plants. In Las Lomas and La Paloma SP/MRF plants, the recyclable materials are recovered, while the OF is separated and sent for biomethanization. The fraction with a sufficiently calorific value (refuse-derived fuel, RDF) is sent to the WtE plant while the rejects of the different processes are sent to the landfill. In the Las Dehesas SP/MRF plant, the valuable materials are recovered and the OF is composted. The rejects with a sufficiently calorific value (RDF) are sent to WtE plant and the rest of the rejects go directly to the landfill.

F2 enters into La Paloma and Las Dehesas SP/MRF plants, where materials are recovered to be recycled and other two fractions are produced: RDF to WtE plant and rejects to the landfill (AM, 2014b).

The WtE plant produces electricity that is exported to the electrical grid. The biomethanization plants generate biogas that is partly purified and injected into the natural gas distribution network. The biogas recovered from the landfill, along with the remaining biomethanization gas, is burned at the La Galiana plant to generate electricity. Part of this electricity is self-consumed and the rest is also exported to the electrical grid. The composting plant produces compost that is sold as an organic amendment that can replace fertilizers (AM, 2014b).

2.2.2. Alternative scenarios

Table 1 shows the alternative scenarios proposed. These are ideal scenarios in which MSW collected (F1, F2, F3 and F4) and the fractions within these types (OF, recyclable materials and rest of materials) are completely processed using the defined treatments in each scenario. In some cases, these scenarios are impossible or improbable within the European Union (EU), though they are of interest to the comparison that is considered in this paper, and even to compare with situations that may arise in countries outside the EU.

2.3. Life cycle assessment – carbon footprint

The LCA methodology was used to quantify the CF of MSW treatment stage, according to the following standards:

- LCA standards: ISO 14040/14044 (ISO, 2006a, b)
- CF standards: ISO/TS 14067 (ISO, 2013), PAS 2070:2013 and 2050:2011 (BSI, 2013, 2011), and Global Protocol for Community-Scale GHG Emission Inventories (WRI, 2014).

2.3.1. Goal and scope definition

This work applies the LCA methodology to MSW treatment stage in Madrid city. Results obtained in the study can help policy makers to reduce the CF of the MSWM (Buratti et al., 2015), and thereby the CF of the city as a whole (BSI, 2013; WRI, 2014). They were also compared with the nine alternative scenarios described in Section 2.2.2.

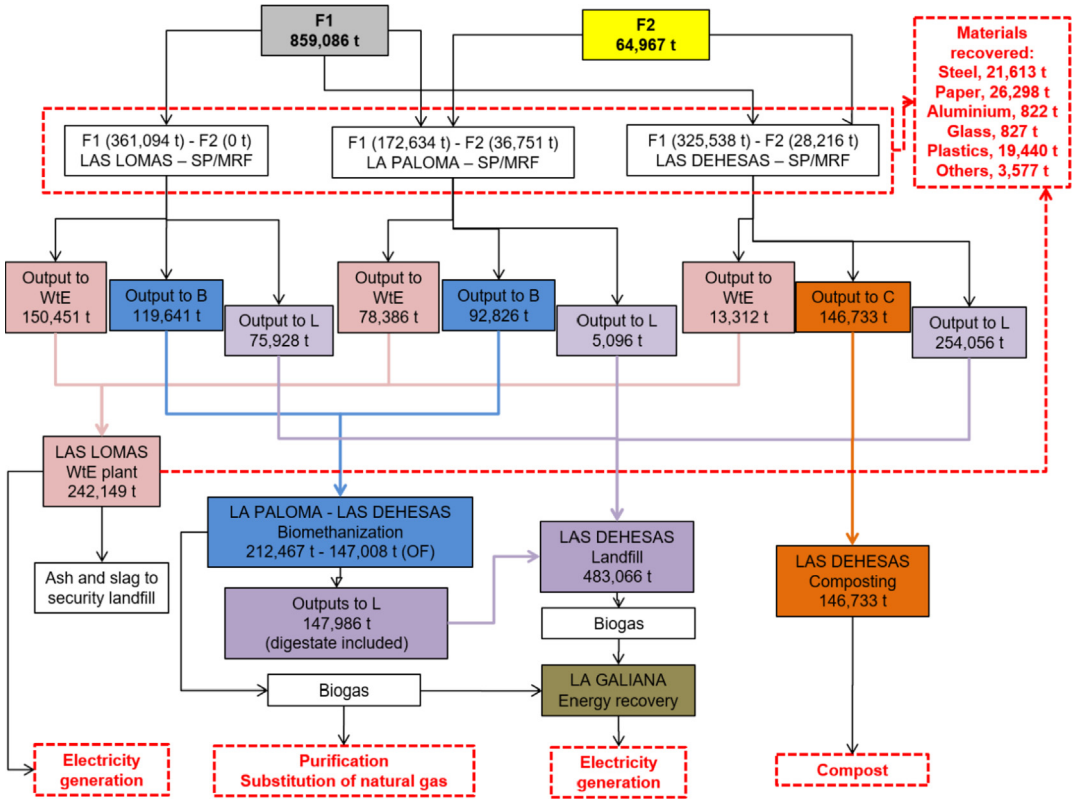
F1
859,086 t
F2
64,967 t
Materials recovered:
Steel, 21,613 t
Paper, 26,298 t
Aluminium, 822 t
Glass, 827 t
Plastics, 19,440 t
Others, 3,577 t
F1 (361,094 t) - F2 (0 t)
LAS LOMAS – SP/MRF
F1 (172,634 t) - F2 (36,751 t)
LA PALOMA – SP/MRF
F1 (325,538 t) - F2 (28,216 t)
LAS DEHESAS – SP/MRF
Output to WtE 150,451 t
Output to B 119,641 t
Output to L 75,928 t
Output to WtE 78,386 t
Output to B 92,826 t
Output to L 5,096 t
Output to WtE 13,312 t
Output to C 146,733 t
Output to L 254,056 t
LAS LOMAS WtE plant 242,149 t
LA PALOMA - LAS DEHESAS Biomethanization 212,467 t - 147,008 t (OF)
LAS DEHESAS Landfill 483,066 t
LAS DEHESAS Composting 146,733 t
Ash and slag to security landfill
Outputs to L 147,986 t (digestate included)
Biogas
Biogas
LA GALIANA Energy recovery
Electricity generation
Purification Substitution of natural gas
Electricity generation
Compost

Fig. 1. Overview of the operation of the VTP (WtE = Waste-to-energy plant, C = composting, B=Biomethanization, OF=Organic fraction, L = Landfill).

Table 1
Alternative scenarios proposed.

Scenario (Acronym)	Description	OF in F1	OF in F2	Packaging in F1	Packaging in F2	Rest of F1 & F2	F3	F4
WtE/Incineration (WtE)	All fractions, except F4, are incinerated with energy recovery	WtE						R
WtE/Incineration + Recycling (WtE + R)	F3 and F4 are recycled, and 100% of the recyclable materials in F2 are recovered. F1, along with the rejects from F2, are incinerated with energy recovery	WtE		R		WtE	R	
WtE/Incineration + All Recycling (WtE + aR)	This differs from the above in that 100% of the recyclable materials in F1 are also recovered. In this scenario, as in the two previous ones, the power generation efficiency is the same as in the current scenario, and the need for auxiliary fuel (diesel) is calculated assuming: 1-minimum calorific values allowed as per the Reference Document on the Best Available Techniques for Waste Incineration (EC, 2006) 2-calorific values for each MSW component according to Gómez et al. (2010)	WtE		R		WtE	R	
Total disposal (L)	All the MSW are sent directly to landfill, where the biogas produced is captured under the same conditions as in the current scenario (a recovery rate of 70%)	L						
Landfilling + Recycling (L + R)	F3 and F4 are recycled together with 100% of the recyclable materials from F2. F1, as well as the rejected F2 fraction, are landfilled	L		R		L		R
Landfilling + All Recycling (L + aR)	This differs from the above in that 100% of the recyclable materials are also recovered from F1	L		R		L		R
Total disposal without biogas recovery (LwBr)	Extreme scenario in terms of GHG emissions, since all fractions are landfilled with no biogas capture	L						
Composting (C + aR)	All the OF is composted and all the recyclable materials in F1 and F2 are recovered. F3 and F4 are sent directly to recycling plants. The rejects from F1 and F2 are landfilled with biogas recovery	C		R		L		R
Biomethanization (biogas replacing natural gas) and composting (B + C + aR)	All the OF in F1 and F2 is biomethanized. The resulting biogas is purified, concentrated and injected into the natural gas distribution network (Ardolino et al., 2018; Budzianowski, 2016). All the recyclable materials from F1 and F2 are recovered, and F3 and F4 are sent directly to recycling plants. The rejects from F1 and F2 are landfilled with biogas recovery. The digestate is mixed with gardening waste and composted (Martínez-Blanco et al. (2010)	B and C		R		L		R

B=Biomethanization; C=Composting; L = Landfilling; OF=Organic Fraction; R = Recycling; WtE = waste-to-energy (incineration with energy recovery).

2.3.1.1. System boundaries. The study was limited to the MSW treatments and technologies implemented in the city of Madrid, and took into account the four main MSW fractions, collected separately (F1, F2, F3 and F4). The other MSWM stages (pre-collection and collection/transport) have been considered in previous investigations (Pérez et al., 2017a, b).

The following GHG emissions were considered:

- direct GHG emissions produced in waste treatment (d-GHGe), taking place within the city boundary: scope 1 emissions as per BSI (2013, 2011) and WRI (2014).
- indirect GHG emissions related to the use of grid-supplied electricity, and fuel production and distribution (i-GHGe): scopes 2 and 3 emissions as per BSI (2013, 2011) and WRI (2014).
- avoided GHG emissions (a-GHGe) as a result of the products obtained (if any) that can replace other products or the raw materials used to produce them (Erses Yay, 2015; Fei et al., 2018; Ferreira et al., 2017; Parkes et al., 2015).

Due to a lack of information, the construction/dismantling of the MSW treatment facilities was not considered (Vedrenne et al., 2014).

2.3.1.2. Time frame and geographical scope. Year 2013 has been used as the characteristic year of MSWM in Madrid city as there was no important change from 2013, and it is the last year with available data. MSW treatments were considered based on the technology in use at that year.

2.3.1.3. Functional unit. One metric ton of treated MSW was established as the functional unit, to compare the different waste treatments and scenarios evaluated. Consequently, CF is expressed in kg CO_2 eq/t_{MSW}.

2.3.2. Life cycle inventory (LCI)

2.3.2.1. Input data. The amount of MSW collected is shown in Fig. A1 (Appendix). Table 2 shows the composition of the two fractions treated at the VTP (AM, 2014b) as a key parameter to

Table 2
Composition of F1 and F2 (AM, 2014b).

	F1 (%)	F2 (%)
OF	26.52	8.97
Pruning and gardening-waste	11.62	1.1
Ferrous metals	2.17	7.8
Non-ferrous metals	0.24	1.16
Paper and cardboard	17.43	15.69
Plastics	14.56	40.2
Liquid-packaging-board-container	0.77	7.62
Glass	3.14	2.64
Wood	2.61	0.92
Textile	7.78	3.8
Cellulosic material	6.83	5.08
Others	6.33	5.02
TOTAL	**100.00**	**100.00**

Table 3
LCI data. F1 and F2 material and energy flows.

		Data, unit	Amount	Source
SP/MRF	Inputs	F1 input, t	859,086	a
Las Dehesas (F1, F2)		F2 input, t	64,967	a
Las Lomas (F1)		Electricity consumption from grid, kWh	8,484,127	b
La Paloma (F1, F2)		Diesel-oil, mobile machinery, t	917	c
	Outputs	Output to landfill, t	335,080	a
		Output to biomethanization, t	212,467	
		Output to WtE plant, t	242,149	
		Output to composting, t	146,733	
	Materials recovered, t	Paper and cardboard	26,298	a
		Steel	17,276	
		Plastics	19,440	
		Glass	827	
		Aluminum	822	
		Other ferrous metals	4337	
		Other packaging metals	765	
		Liquid-packaging-board-container	2812	
WtE plant	Inputs	Inputs from Las Lomas SP, t	150,451	a
Las Lomas		Inputs from La Paloma SP, t	78,386	
		Inputs from Las Dehesas SP, t	13,312	
		Total MSW to WtE plant, t	242,149	
		Diesel-oil, auxiliary fuel, t	964	d
		MSW net calorific value, GJ/t	14.75	
		Diesel-oil, net calorific value	43.33	
	Outputs	Gross electricity production, MWh	166,977	d
		Net electricity production, MWh	117,337	d
		Slags to landfill, t	9397	a
		Ashes to security landfill, t	17,439	a
Composting plant	Inputs	Input from Las Dehesas SP	146,733	a
Las Dehesas		Electricity consumption from grid, kWh	9,510,114	e
		Diesel-oil, mobile machinery, t	17	f
	Outputs	Generation of compost, t/t	0.27	g
Biomethanization plants	Inputs	Input from La Paloma SP, t	119,641	a
La Paloma		Input from Las Lomas SP, t	92,826	
Las Dehesas		OF to anaerobic digestion, t	147,008	
		Electricity consumption from grid, kWh	16,483,272	h
		Diesel-oil, mobile machinery, t	81	
	Outputs	Reject to landfill, including digestate, t	147,986	a
		Purified biogas to natural gas distribution network (98% CH_4), Nm^3	1,852,326	
		Biogas to electricity generation with landfill biogas at La Galiana (61% CH_4), Nm^3	13,227,271	
Landfill and biogas valorization	Inputs	Reject from Las Lomas SP, t	75,928	a
Las Dehesas landfill		Reject from La Paloma SP, t	5096	
La Galiana		Reject from Las Dehesas SP, t	254,056	
		Outputs from biomethanization plants, t	147,986	
		Total MSW to landfill, t	483,066	
		Diesel-oil, mobile machinery, t	386	i
		Natural gas, auxiliary fuel, t ([a])	199	a
	Outputs ([a])	Landfill biogas recovered, Nm^3	30,330,370	d
		Gross electricity production, MWh	65,194	
		Net electricity production, MWh	59,190	

a) AM (2014b).
b) Average values from Bovea et al. (2010), Fernández-Nava et al. (2014), Herva et al. (2014): 9.18 kWh/t_{MSW}.
c) Average values from Bovea et al. (2010) and Fernández-Nava et al. (2014): 1 kg/t_{MSW}.
d) AM (2015b).
e) Average values from Bovea et al. (2010), Buratti et al. (2015), Erses Yay (2015), Fernández-Nava et al. (2014), Habib et al. (2013), Herva et al. (2014), Martínez-Blanco et al. (2010), Song et al. (2013): 64.81 kWh/t_{MSW}.
f) Average values from Bovea et al. (2010), Erses Yay (2015), Fernández-Nava et al. (2014), Martínez-Blanco et al. (2010), Song et al. (2013): 3.9 kg/t_{MSW}.
g) Average values from Buratti et al. (2015), Erses Yay (2015).
h) Fernández-Nava et al. (2014).
i) Average values from Fernández-Nava et al. (2014): 0.8 t/t_{MSW}.
[a] These amounts refer to the natural gas used as an auxiliary fuel and to the electricity generated from the valorization of the biogas recovered from the waste landfilled prior to 2013, but not in 2013 itself.

assess the life cycle of MSWM solutions (Bisinella et al., 2017). Table 3 shows the main inputs and outputs for each treatment.

As noted in Section 2.1, F3 and F4 are sent directly to recyclers for recovery. Since no data are available for the city of Madrid, it was assumed that 85.5% of F3 is paper and cardboard, and that 94% of F4 is glass, being the rest impurities (Rigamonti et al., 2009). Separation plants for F3 and F4 require electricity and diesel. Given the lack of specific information for Madrid, a consumption of 9.18 kWh of electricity and 1 kg_{diesel}/t_{MSW} was assumed, according to Fernández-Nava et al. (2014) and Herva et al. (2014).

The sources of GHG emissions for each treatment are summarized in Table 4.

2.3.2.2. d-GHGe

2.3.2.2.1. Mobile machinery. d-GHGe from mobile machinery used in all treatment plants were calculated using the emissions

Table 4
GHG emissions sources.

	d-GHGe	i-GHGe	a-GHGe
SP/MRF	Mobile machinery combustion	Electricity consumption from distribution network and fuel production/distribution out-of boundary (consumed in mobile machinery)	Raw materials avoided for materials recovered
WtE plant	MSW and auxiliary fuel incineration	Fuel production/distribution out-of boundary (consumed as an auxiliary fuel)	Electricity
Composting	Composting process and mobile machinery combustion	Electricity consumption from distribution network and fuel production/distribution out-of boundary (consumed in mobile machinery)	Chemical fertilizers for compost
Biomethanization	Anaerobic digestion process and mobile machinery combustion	Electricity consumption from distribution network and fuel production/distribution out-of boundary (consumed in mobile machinery)	Electricity and/or natural gas replaced by biomethane
Landfill and biogas valorization	Biogas from anaerobic decay of MSW deposited, mobile machinery combustion and biogas and auxiliary fuel combustion	Fuel production/distribution out-of boundary (consumed in mobile machinery and as an auxiliary fuel)	Electricity

Table 5
d-GHG emissions factors.

	CO_2	CH_4	N_2O	Source
Mobile machinery, diesel (g/t_{diesel})	3138	32	136	EEA, 2013
WtE plant, MSW (g/t_{MSW})	IPCC model	138	50	IPCC, 2006
WtE plant, diesel, co-combustion (g/GJ)	74,100	3	0.6	
Composting, g/kg_{waste}, wet weight basis	0 (biogenic)	4	0.24	
Biomethanization, g/kg_{waste}, wet weight basis	–	0.8	negligible	
Biogas combustion, engines, g/t CH_4	0 (biogenic)	28,000	90	
Natural gas combustion, $g/GJ_{natural\ gas}$	56,000	316	1.3	

factors (EF) provided in the EMEP/EEA Guidebook (EEA, 2013) (Table 5).

2.3.2.2.2. WtE plant. The WtE plant consists of a bubbling fluidized bed. Its d-GHGe depend, simultaneously, on MSW and auxiliary fuel combustion. CO_2 emissions from the burning of MSW were calculated using IPCC methodology, taken from the IPCC Guidelines for National GHG Inventories (IPCC, 2006). To apply this methodology, the composition of the incinerated waste was considered from AM (2014b), and the dry matter, total carbon and fossil carbon (FC) contents of each fraction were taken from the IPCC (2006), as shown in Table 6.

CH_4 and N_2O emissions from waste incineration and those associated with the combustion of auxiliary fuel were calculated using the EF proposed by the IPCC (2006), Table 5.

2.3.2.2.3. Composting and biomethanization. d-GHGe from aerobic and anaerobic digestion were calculated according to IPCC (2006), and are shown in Table 5. In both cases, CO_2 emissions are of biogenic origin and do not count toward the overall result.

2.3.2.2.4. Landfill. Controlled landfills produce emissions due to the biogas that is emitted by the decomposing OF deposited in them. Even though this biogas mainly contains CO_2 and CH_4, only the CH_4 should be considered because the CO_2 emissions are of biogenic origin (IPCC (2006); EEA (2013)).

Biogas production was estimated using IPCC methodology. It assumes that the tons of waste landfilled in a year will decompose over the following years, generating CH_4. To calculate total CH_4 generation, the degradable organic carbon (DOC) Is determined from the composition of the deposited waste. Table 7 shows the waste composition considered (AM, 2015a) and other parameters required to estimate biogas production using IPCC methodology.

Around 70% of the biogas generated in the Las Dehesas landfill is recovered (AM, 2015a, 2014b). This biogas is used in combination with natural gas to produce electricity in stationary engines at the La Galiana plant (AM, 2015b). GHG emissions associated with biogas/natural gas combustion were calculated using the EF reported in IPCC (2006) and EEA (2013) (Table 5). In contrast, the non-recovered fraction (30%) is emitted into the atmosphere. The biogas capture rate is in line with Vergara et al. (2011), who found recovery

Table 6
Parameters used to calculate d-GHGe from WtE plant.

	Percentage composition (%)	Dry content (%)	Total carbon content (% on dry weight basis)	Fossil carbon, FC (%, total carbon content)	Oxidation factor (%)
Paper and cardboard	16.7	90	46	1	100
Textile	29.4	80	50	20	100
Food waste	9.7	40	38		100
Wood	6.7	85	50	0	100
Pruning and gardening waste	2.0	40	49	0	100
Cellulosic wastes	8.6	40	70	10	100
Rubber and leather	2.3	84	67	20	100
Plastics	21.0	100	75	100	100
Metals	0.7	100	0	0	100
Glass	0.4	100	0	0	100
Others (inert)	2.5	90	3	100	100

Table 7
Landfill disposal. Composition of waste disposed into the landfill and IPCC default values to estimate CH_4 generation and emission.

Component	% (mass)
OF (food wastes and similar)	9.1
Paper	19.8
Diapers/Cellulosic materials/Textiles	8.3
Wood	1.4
Gardening and pruning waste	9.6
Resulting degradable organic carbon (DOC)	14
IPCC (2006) **default values for other parameters**	
Methane correction factor (MCF)	1
Methane generation rate constant (k)	0.05
Methane/Biogas volume fraction (Fi) (data from AM, 2015b)	0.56
Oxidation factor (OX)	0.1

rates of 64% for landfills in California.

2.3.2.3. i-GHGe. Spain's electricity generation mix (REE, 2014; Table A2, Appendix) emits 0.29 kg CO_2 eq/kWh that is used to estimate i-GHGe from the consumption of electricity in those treatments that require electricity from the grid (MINETUR, 2014).

i-GHGe from fuel production and distribution ("cradle-to-gate") were calculated as per López et al. (2009), where consumption factors were deduced based on the characteristics and supply conditions in Madrid. GHG emissions are 10.2 g CO_2 eq/t_{diesel} and 9.7 g CO_2 eq/$MJ_{natural\ gas}$.

2.3.2.4. a-GHGe. MSW treatments generate different products such as fuel, compost and electricity, which can replace other products or services (or the same products obtained by another method), thereby a-GHGe associated with their generation and/or production processes (Habib et al., 2013; Parkes et al., 2015).

a-GHGe per unit of recovered material are listed in Table A3(Appendix), and are based on the replacement rates for recovered materials/raw materials, deduced from the separation efficiency and the recycling efficiency for each of the fractions recovered (Rigamonti et al., 2009).

In the case of electricity generation, each unit of energy sent to the electrical grid replaces the electricity generated by the marginal source of energy that covers the demand, as required by a LCA consequential approach (Bernstad Saraiva et al., 2017). In the case of Spain's electrical grid, natural gas is the marginal energy source (REE, 2014). Therefore, each kWh generated and sent to the grid avoids the emission of 0.355 kg CO_2 eq (Lumbreras et al., 2009).

Purified biogas (biomethane) from anaerobic digestion can replace natural gas. The a-GHGe from its combustion are 65.7 kg CO_2eq/$GJ_{biomethane}$, including the whole natural gas life cycle; 56 kg/GJ from combustion process (IPCC, 2006) and 9.7 kg/GJ from production and distribution (López et al., 2009).

2.3.3. Life cycle impact assessment (LCIA)

The adopted LCIA methodology was IPCC-Fifth Assessment Report, using the Global Warming Potential (GWP) with a 100-year horizon (IPCC, 2013) as characterization factor. The impact category indicator used is CO_2 equivalent emissions, estimated as the weighted average of the emissions of each GHG and their corresponding GWP.

3. Results and discussion

3.1. Current scenario

Fig. 2 shows the GHG emissions associated with the current scenario, sorted by type of treatment and emission (Table A4 shows the calculated emissions by treatment and gas).

Total emissions were 226 kt CO_2 eq. This figure is obtained by summing up the values for d-GHGe (443 kt) and i-GHGe (10 kt CO_2 eq), and then subtracting a-GHGe (227 kt CO_2 eq). As for the treatments, landfill with biogas recovery exhibits the highest emissions (193 kt), followed by WtE treatment with 132 kt. The composting treatment adds 27 kt, while emissions from biomethanization are −14 kt, which shows that a-GHGe are higher than d-GHGe + i-GHGe. In terms of functional unit, the impact on CC is equal to 224 kg CO_2 eq/t_{MSW}.

Fig. 3 shows treatment's contribution to each emission type. 51.8% of d-GHGe is due to landfilling with recovery and use of the biogas generated. These emissions are determined by the DOC of the landfilled waste, which has been decreasing in recent years. Since 2011, large amounts of have been treated by biomethanization. In 2013, only 9.1% of the landfilled waste was OF (Table 7).

The second most important contributor to d-GHGe is the WtE plant, accounting for 39.3%. These emissions are conditioned by the percentage of biogenic carbon contained in incinerated waste, which is equal to 56% for this scenario.

As for i-GHGe, the biomethanization process and the subsequent purification of the resulting biogas account for 46.9%. This is followed by composting, which contributes 27.1%. These high percentages are due to the electricity consumed by these plants, which are not self-sufficient, unlike the WtE plant and the landfill with biogas recovery.

SP/MRF plants account for 50.9% of the a-GHGe. This is due to the recovery of recyclable materials. They are followed by the WtE process and the biogas valorization in landfill, which contribute to 18.4% and 15.8% of the a-GHGe, respectively, as a consequence of their electricity generation.

3.2. Alternative scenarios

The results obtained for the nine alternative scenarios proposed are shown in Fig. 4 (Table A5, Appendix, shows the calculated emissions by scenario and gas). As expected, the LwBr scenario exhibits the greatest impact (1821 kg CO_2 eq/t_{MSW}, Fig. 4a), and it is 712% above the current scenario (Fig. 4c). This value stems from the fact that all of the MSW is landfilled and the CH_4 generated is not recovered, causing the increase in d-GHGe (Fig. 4b). Moreover, since the biogas generated is not recovered, no electricity is generated, and thus the electricity consumed must be supplied externally. These results confirm those found by Buratti et al. (2015), Erses Yay (2015), and those compiled by Cleary (2009). This is not the case in Madrid where the biogas is recovered, which considerably reduces the CF. This reduction is conditioned by the CH_4 recovery rate (Vergara et al., 2011) and the composition of the disposed MSW. As it was previously mentioned, in the current scenario the recovery rate is 70% and most of the biodegradable material is not landfilled (AM, 2015a, 2014b).

In the L scenario, all of the MSW is landfilled and the biogas is recovered under the same assumptions as in the current scenario. In this case, CF is 510 kg CO_2 eq/t_{MSW}, which represents a reduction of 70% with respect to the LwBr scenario, analogous to the biogas recovery rate considered.

The L + R scenario has a CF that is 57% higher than current scenario (353 kg CO_2 eq/t_{MSW}). This is because even though the recyclable materials from fractions F2 to F4 are recovered, all of the OF is landfilled, which raises d-GHGe of CH_4. Total emissions for this scenario are 31% lower than for the L scenario. If the recyclable materials present in the F1 fraction are recovered (scenario L + aR), the CF yields a negative value (−88 kg CO_2 eq/t_{MSW}), meaning that

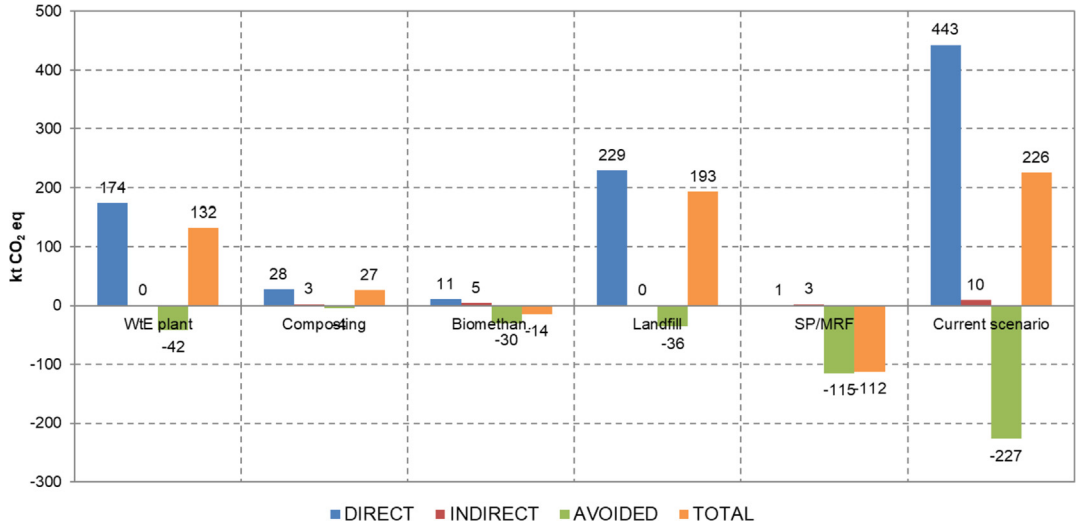

Fig. 2. GHG emissions of the current scenario.

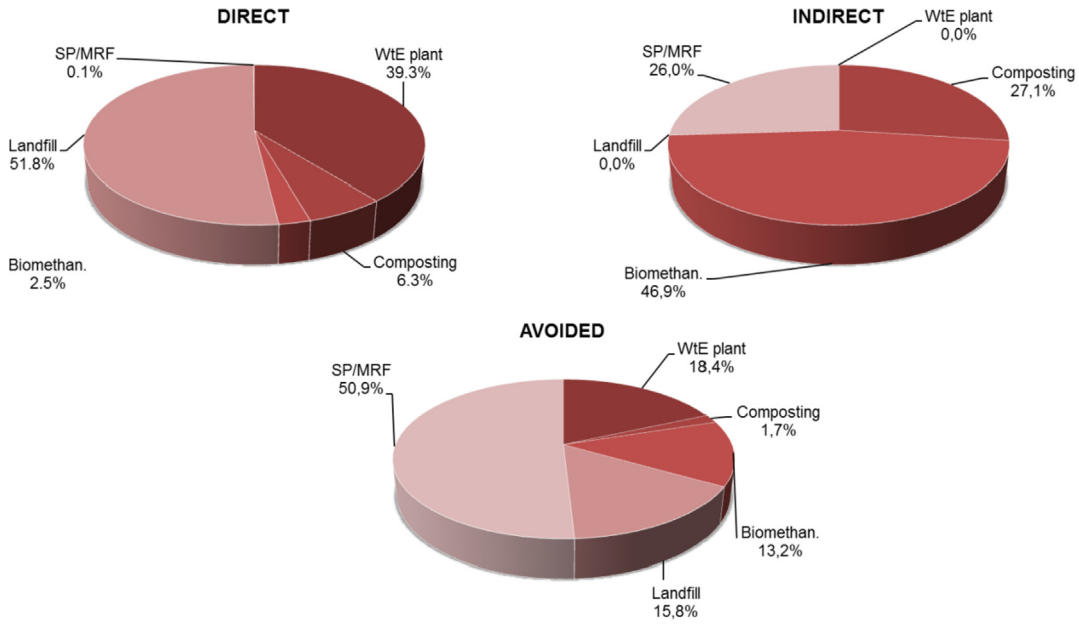

Fig. 3. Direct, indirect and avoided GHG emissions distribution in current scenario.

a-GHGe exceed the sum of d-GHGe and i-GHGe.

The WtE treatment is included in three alternative scenarios. The WtE scenario has a CF of 306 kg CO_2 eq/t_{MSW}, which is a 36% above the current scenario. This is due to the increase in d-GHGe and the decrease in a-GHGe (electricity is generated, but recyclable materials are not recovered). In the WtE + R scenario, all of the recyclable materials present in F2 to F4 fractions are recovered, which increases a-GHGe and reduces d-GHGe. This scenario has a CF that is 12% lower than the current scenario. The WtE + aR scenario has the lowest impact on CC, with a CF of −219 kg CO_2 eq/t_{MSW}, 198% less than the current situation. This scenario involves recovering all of the recyclable materials contained in the MSW as a whole, hence the increase in a-GHGe with respect to the other two scenarios in which WtE treatment offers an alternative. In this last scenario, the fractions sent to the WtE plant are mainly those with a zero or very low FC content: OF (43% and 0% FC), landscaping waste (18% and 0% FC), textiles (13% and 20% FC), cellulosic material (11% and 10% FC) and wood (4% and 0% FC). As a result, their "computable" d-GHGe are considerably reduced despite the increase in the emissions associated with the auxiliary fuel. The amount of diesel required rises as a consequence of the lower calorific value of the RDF fed into the process, which is below that of the other scenarios that include WtE treatment.

The scenarios where all recyclable materials are recovered from the four fractions and the OF is biologically treated exhibit negative CF values: −148 and −249 kg CO_2 eq/t_{MSW} for the C + aR and B + C + aR scenarios, respectively. The B + C + aR scenario exhibits the greatest environmental benefit in terms of CC, as it makes the most use of the OF contained in the MSW. This is because the digestate generated in the methanization process is mixed with gardening waste and undergoes a composting process (Martínez-Blanco et al., 2010). The compost produced replaces the use of

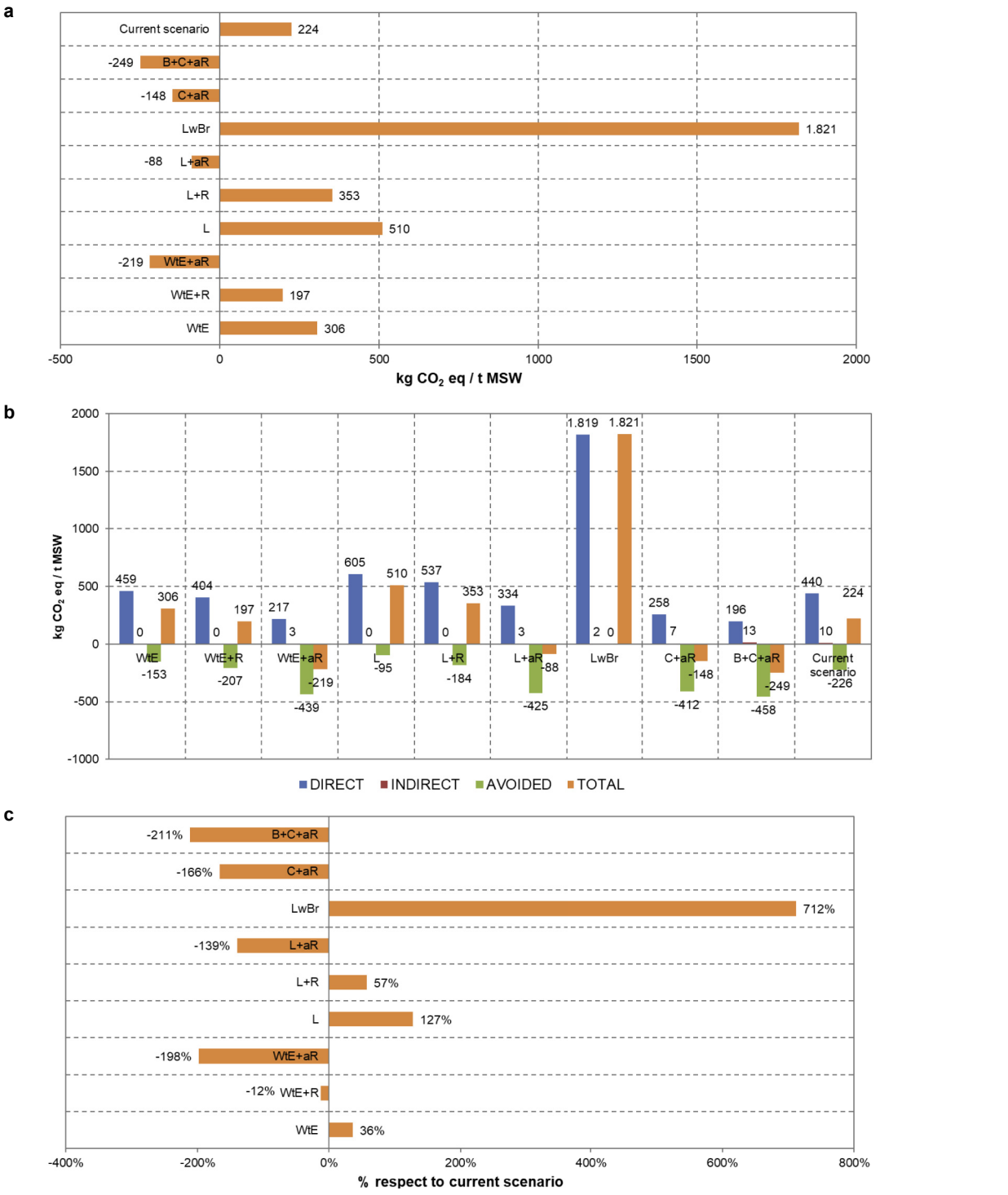

Fig. 4. Comparison between scenarios. (a) CF for each scenario. (b) CF disaggregated per type of GHG emission considered. (c) Status of each scenario with respect to current scenario.

fertilizers, and thus the a-GHGe are increased with respect to other scenarios (Manfredi and Pant, 2013). These results confirm those found by Fei et al. (2018).

3.3. Sensitivity analysis (SA)

According to the ISO standards and the International Reference Life Cycle Data System Handbook (EC-JRC-IES, 2012), a SA is required in order to determine the influence of main assumptions in final results.

One of the main hypotheses considered in this work is the recovery rate for CH_4 in the landfill (70%, AM, 2015a). A change in this recovery rate would produce an inversely proportional effect on d-GHGe and a directly proportional effect on a-GHGe: a change in the CH_4 recovery from 50% to 90% would result in a CF for the current scenario ranging between 365 and 84 kg CO_2 eq/t_{MSW} (change of

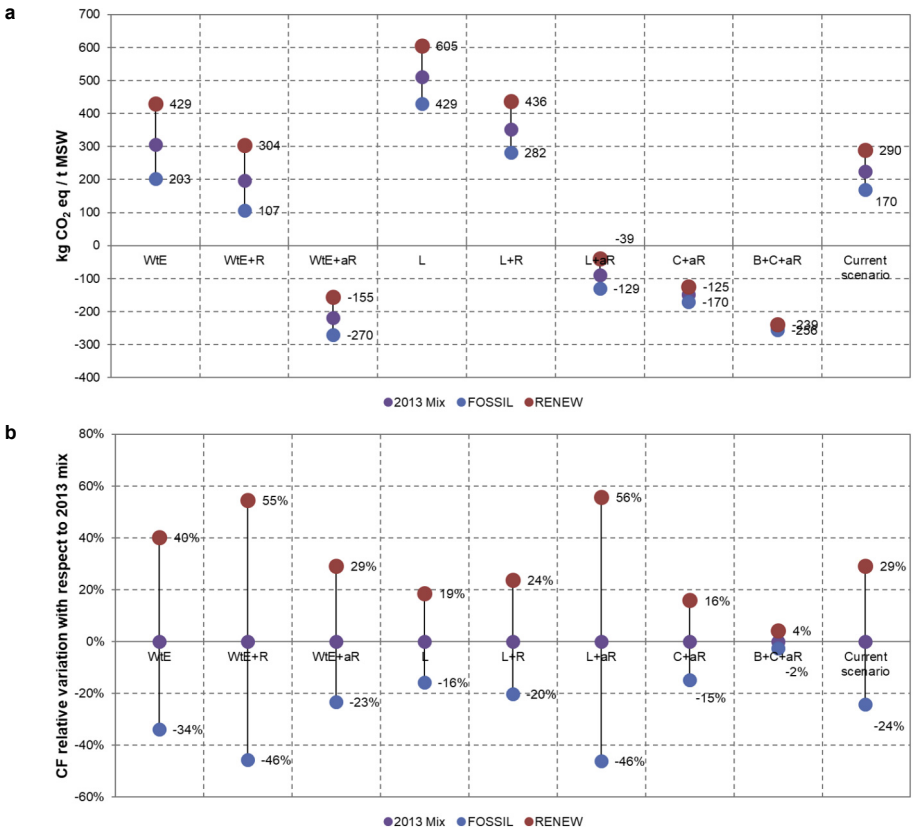

Fig. 5. SA: influence of electricity generation mix. (a) Total CF variation. (b) Relative CF variation depending on electricity generation mix.

±63%).

When waste treatment requires electricity consumption, the CF figure is influenced by the energy mix used to generate electricity (Vergara et al., 2011). The magnitude of i-GHGe, therefore, depends on the amount of electricity generated from fossil sources, more intensive in GHG emissions per unit of electricity generated than nuclear and renewable sources, and also on the performance of the technologies used (combined cycles, conventional power plants, etc.). This study considered Spain's energy mix for 2013, whose average emissions rate was 0.29 kg CO_2 eq/kWh. In that year, renewable energies accounted for 40.7% of the electricity produced, while nuclear energy and fossil fuels represented 19.9% and 39.5%, respectively (REE, 2014).

Fig. 5a shows the influence of the electricity generation mix on the results. Two extreme alternatives were compared to the 2013 mix: having 100% of the electricity generated either by renewable sources (RENEW) or by fossil sources (FOSSIL), with conventional thermal coal plants and natural gas in combined cycle plants each providing 50% of the total generation. The highest relative differences (Fig. 5b) are more evident in those scenarios in which a-GHGe from electricity generation are important (scenarios that include WtE and/or landfilling with energy recovery).

When electricity is generated using fossil fuels, every scenario (except the LwBr scenario, not shown in Fig. 5 due to the scale) has a lower impact on CC than with the 2013 Mix, whereas when renewable sources are used, the opposite is true. This apparent contradiction underscores that a-GHGe are more relevant than i-GHGe. In every scenario proposed except for LwBr, electricity is produced in WtE plants or by biogas recovery in landfills. The only scenario with the opposite situation is the LwBr scenario, where biogas is not recovered, and thus electricity is not produced, so demand is satisfied with electricity supplied from the grid. Therefore, if electricity were generated entirely by renewable sources, the CF would drop to 1819 kg CO_2 eq/t_{MSW}, and if it were generated entirely from fossil fuels, it would rise to 1824 kg CO_2 eq/t_{MSW} (versus the 1821 kg CO_2 eq/t_{MSW} for the 2013 Mix, Fig. 5a).

4. Conclusions

This study proposes a simple methodology to evaluate CF for the MSW treatment stage, using a major European city like Madrid as a case study. It also compares the current situation with nine alternative scenarios. This comparison can be used to evaluate if one particular waste treatment method is more environmentally friendly (in terms of CF) than other alternatives in a given municipality.

It was found that the current scenario has a CF of 224 kg CO_2 eq/t_{MSW}, an 88% lower figure than worst situation (LwBr scenario), in which MSW are landfilled with no biogas recovery. The scenario with the lowest EI on CC is the B + C + aR scenario, with a CF of −249 kg CO_2 eq/t_{MSW}. These two extreme scenarios are ideal and hypothetical, since they require separating 100% of the component fractions and processing it using the selected treatment. Such a level of separation is impossible to achieve from a practical standpoint.

Based on the results, the CF of current MSW treatment in Madrid is considerably closer to the best situation, evidence of the success of the MSW plans and programs implemented both locally (AM,

2014c) and regionally (CM, 2014).

Results also show that those scenarios with recyclable materials recovery in all four fractions of household waste, in combination with biological or WtE treatments, are the options that have the lowest CF: B + C + aR and WtE + aR scenarios (in line with Fei et al., 2018). Their CF values are negative because a-GHGe are higher than direct emissions.

The SA carried out allows to conclude that if the electricity in Spain were generated entirely using fossil fuels, every scenario (except for LwBr) would have had a lower impact on CC, compared with the results from the 2013 mix. In contrast, if the electricity were generated using renewable sources, the CF would have increased. This finding underscores the greater importance of a-GHG over i-GHGe. The only scenario in which the opposite is true is the LwBr scenario in which, since the biogas is not recovered, no electricity is produced, so power demand is supplied from the electrical grid.

Some limitations were found during this study. The first involves the lack of specific information on the energy consumption of SP/MRF, composting and anaerobic digestion plants, which required resorting to bibliographic data to estimate those consumptions. Another limitation of the study is related with the installed production capacities, since no potential needed increase in capacity for any of the alternative scenarios proposed was considered (and its associated EI). Finally, it is assumed that biogenic emissions of CO_2 do not have a global warming potential, according to IPCC (2006) recommendations (based on the assumption that in a long-term LCA-perspective, biogenic emissions of CO_2 are balanced by an equivalent biological uptake of CO_2 during plant growth). Some authors, however, have concluded that a significant fraction of the carbon entering landfilling systems, composed almost entirely of biogenic carbon, without plastic-like fractions, remains stored at the end of the LCA time horizon (Manfredi and Christensen, 2009). This carbon, which is still bound in the landfill after 100 years, represents a potential for CO_2 emission after the selected time horizon of the LCA.

The analysis can be expanded to other cities, though local conditions would influence LCA results. By using the same methodology and proposing similar alternative scenarios, obtained results could be compared. These analyses could evaluate different waste composition, which is conditioned by socioeconomic variables, and diverse energy use that is conditioned by market prices and energy policy of each country, region or city.

Future research lines can be oriented to:

- considering the emission of other pollutants and the evaluation of other environmental impacts, both from MSW treatment stage and from the pre-collection and collection/transport stages, previously analyzed in Pérez et al. (2017a; 2017b).
- performing an uncertainty analysis, not only for the MSW treatment stage, but also for the pre-collection and collection/transport stages (discussed in Pérez et al. (2017a, b))
- carrying out an economic analysis of the different scenarios.

Acknowledgements

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APPENDIX. 7.

Table A1
Macroeconomic and main data for the city of Madrid, year 2013 (AM, 2015a, b; 2014a, b; INE, 2015a, b; MAGRAMA, 2015; MINETUR, 2014).

	Madrid	% Madrid/Spain
Population, inhabitants	3,237,937	6.8
Area, km^2	606	0.1
Gross domestic product, M€$_{2000}$	91,019	12.1
Final energy consumption, ktoe	3372	3.8
MSW collected, t	1,115,059	2.1
Direct GHG emissions, kt CO_2 eq	6840	2.1

Table A2
Spain's electricity production mix. Year 2013.

Type	%
Hydraulic	14.4
Nuclear	19.9
Coal	14.6
Natural gas	20.0
Oil products	4.9
Wind	19.6
Solar	4.6
Biomass and wastes	2.1

Table A3
a-GHGe per ton of source-separated material.

	t CO_2eq/t
Paper and cardboard (including liquid packaging board container)	0.56
Plastics	1.12
Glass	0.72
Aluminum	9.85
Steel and other ferrous metals	0.40
Food and green wastes to produce compost (replace inorganic fertilizers)	0.026

Table A4
GHG emissions in current scenario.

	CH_4 (t)	CO_2 (kt)	N_2O (t)	CO_2 eq (kt)
WtE plant	35.88	127.95	12.13	132.17
Composting	586.95	0.84	35.29	26.63
Biomethanization	381.01	−24.98	0.39	−14.21
Landfill	7926.33	−29.05	1.90	193.39
SP/MRF	0.03	−112.38	0.14	−112.34
TOTAL	8930.20	−37.61	49.85	225.65
Carbon footprint (kg CO_2 eq/t_{MSW})				**224.33**

Table A5
GHG emissions in alternative scenarios.

	CH_4 (kt)	CO_2 (kt)	N_2O (kt)	CO_2 eq (kt)	Carbon footprint (kg CO_2 eq/tMSW)
WtE	0.10	292.77	0.05	307.89	306.10
WtE + R	0.09	183.89	0.04	198.10	196.95
WtE + aR	0.04	−229.40	0.03	−220.61	−219.32
L	21.08	−78.38	0.01	513.06	510.07
L + R	18.68	−169.55	0.00	354.68	352.62
L + aR	11.53	−412.55	0.00	−88.98	−88.46
LwBr	65.24	4.98	0.00	1.831.76	1.821.11
C + aR	8.28	−396.13	0.06	−148.92	−148.06
B + C + aR	6.34	−438.12	0.04	−250.82	−249.36
Current scenario	8.93	−37.61	0.05	225.65	224.33

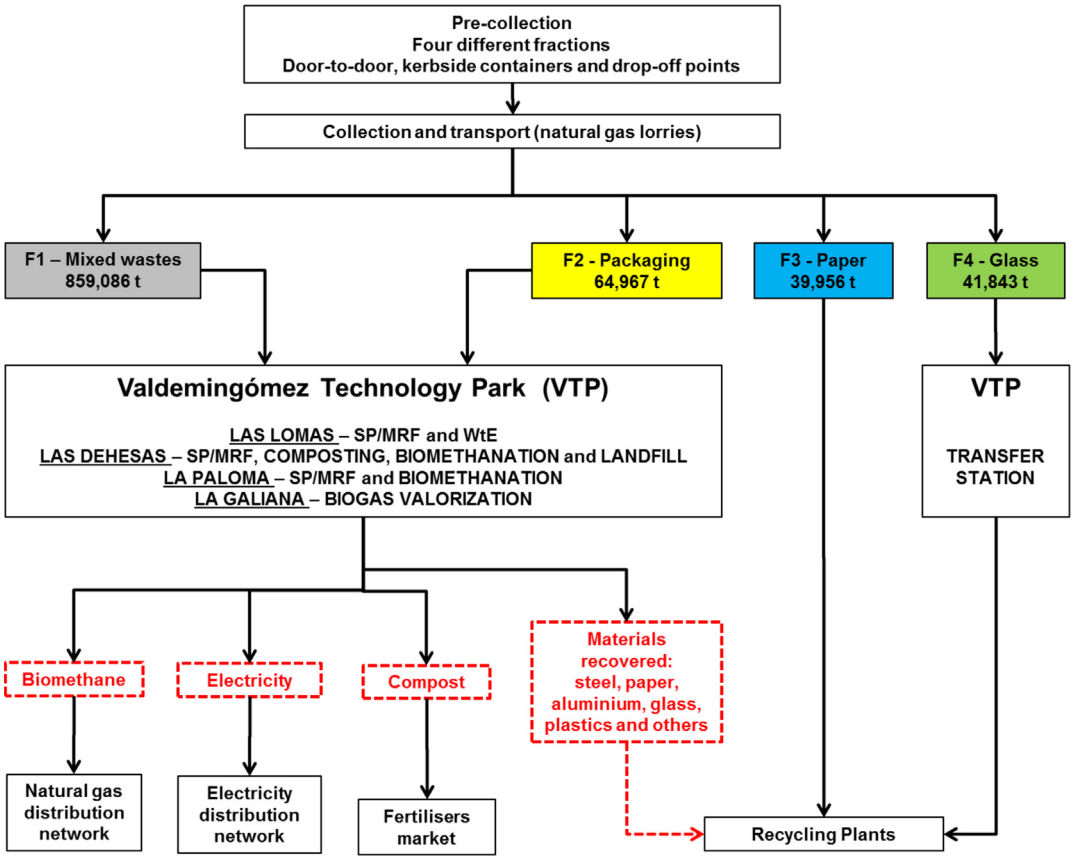

Fig. A1. Basic outline of the integrated management of the four main MSW fractions in Madrid.

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